# EXPERIMENTAL INVESTIGATION ON GAS LASER CUTTING

**M. Prabhakaran[1], A.N. Patil[2], Nagaraj Raikar[3], Sidharth.K[4]**

[1,2,3,4] *Department of Mechanical Engineering, Agnel Institute of Technology and Design, Goa, (India)*

**ABSTRACT**

*Laser beam cutting (LBC) is a most predominantly used non-traditional cutting process to cut desired shapes out of sheet metals, plates, sections and boxes with greater accuracy at least time. The criticality in this process is its complexity in cutting non ferrous materials due to their lesser absorption rate of the laser beam. Continuous wave $CO_2$ laser and pulsed Nd:YAG laser are the most commonly used methods for cutting of non ferrous metal sheets. This experiment investigates the effect of input parameters Laser power (kW), Cutting speed (m/min), Assist gas pressure (bar) and Nozzle standoff distance (mm) on different responses like surface roughness ($R_a$ in µm), kerf width ($K_w$ in mm), dimensional deviation ($D_d$ in mm) and hole diameter ($H_d$ in mm). This entire experiment is designed using Taguchi $L_9$ Orthogonal Array (OA) technique. The data collected are analyzed with the aid of Multiple Regression Analysis (MRA) and Grey Relational Analysis (GRA). The optimized results obtained out of GRA are tested by performing a confirmation experiment.*

***Keywords: $CO_2$ Laser, Grey Relational Analysis, Laser Cutting, Multiple Regression Analysis, Taguchi Method***

## I. INTRODUCTION

Laser is the acronym for Light Amplification by Stimulated Emission of Radiation. Out of the various applications of laser, this study converges towards its industrial application wherein it is used for cutting metal plates and sheets of various thicknesses. The laser cutting operation has numerous advantages over the methods such as shearing, wire cut electric discharge machining, water jet machining, etc. The remarkable properties of laser cutting which makes it more demanding are zero tool wear, narrow kerf width, greater accuracy, ability to be numerically controlled, lesser cutting time and reduced heat affected zone [1].

LBC is a non contact process and the material removal takes place through melting and vaporization of metal when the laser beam comes in contact with the metal surface. The most widely used laser types for cutting of sheet metal are continuous wave $CO_2$ laser and pulsed Nd:YAG laser. Whenever it comes to laser cutting of non ferrous metals such as aluminium, copper and brass, it becomes a complex task due to the less absorptive nature i.e. highly reflective nature of these materials.

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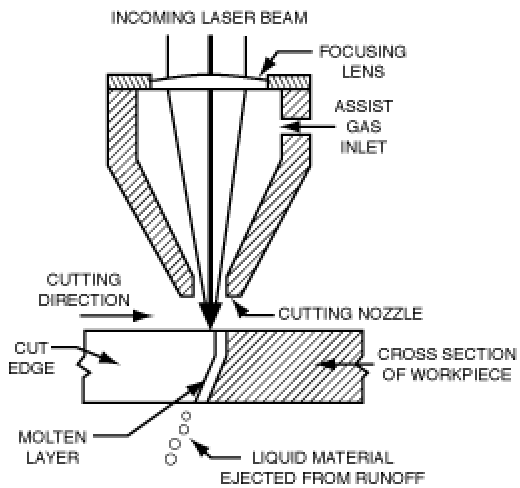


**Fig.1 Laser Beam Cutting**

The industrialists have put greater efforts to get best results of laser cut quality [1-15] and still it remains a mystery for so many non ferrous materials. The $CO_2$ lasers are used since it can generate higher laser power at lower cost irrespective of its higher wavelength of 10.6µm [13]. The Nd:YAG lasers are known for its lower wavelength (1.06µm) and high absorptivity by non ferrous materials.

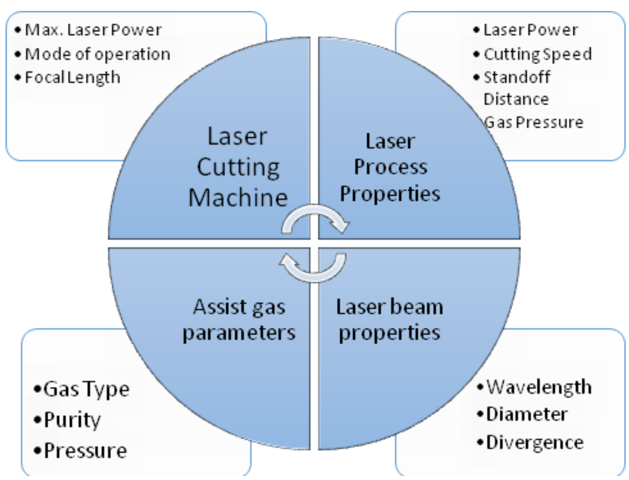


**Fig. 2 Factors affecting the quality of a laser cut**

This proposed study intends to investigate the effect of the input parameters laser power (kW), cutting speed (m/min), assist gas pressure (bar) and nozzle standoff distance (mm) during the laser cutting of aluminium alloy BS 1100 grade. This alloy is widely used for various industrial applications like fabricating casings, hoods, automobile body building, etc. The alloy composition of this material is shown in Table 1.

The success of any laser cutting operation purely banks on the apt selection of the input process parameters. This study experiments the effect of the aforesaid control factors during the cutting process of material under study.

Further using MRA a model has been developed to study the relation between the input parameters and the responses. The collected data is optimized using GRA technique to obtain a better cut.

## II. LITERATURE SURVEY

There are various papers investigating the effect of $CO_2$ laser cutting on various steel grades. Number of researchers have also done study of laser cutting effect on aluminium alloys as well [1,10,13]. Arun Kumar D. and Avanish Kumar D. [1] investigated the laser cutting performance of difficult to laser cut material using pulsed Nd: YAG laser. 1mm duralumin sheet material is used as work material. The experiments were conducted using pulsed Nd: YAG laser and the experiment have been carried out with the aid of Taguchi methodology based $L_{27}$ Orthogonal Array optimization technique.

Amit Sharma and Vinod Yadava [4,8] studied the laser cutting quality of thin aluminium sheet using pulsed Nd: YAG laser for a curved cut profile and straight cut profile. The input parameters taken into consideration were arc radius of curve profile, oxygen pressure, pulse width, pulse frequency and cutting speed and the output quality characteristic considered were average kerf deviation and average kerf taper. The author has developed a response surface model for kerf deviation and kerf taper using hybrid approach of Taguchi Methodology and Response surface methodology. K.Huehnlein et al [11] analyzed the effect of various process parameters on the laser cutting quality of $Al_2O_3$ using fiber and $CO_2$ lasers. For fiber laser 46 individual laser experiments were conducted with five influencing factors in consideration. The authors have made use of design of experiments to find the interaction between all the parameters under study. The various parameters taken for study are laser power, velocity, standoff distance, pressure of the gas and position of the focus.

This experiment has been designed from the literature study by selecting the various input parameters and responses.

## III. EXPERIMENTS

The success factor any experiment is basically based on how well that experiment has been designed. The design of experiments ensures the following benefits:

**Table 1 - Percentage alloy composition of BS1100 (wt%)**

| Si | Fe | Cu | Mn | Mg | Cr | Ni | Zn | Ti | Pb | Sn | Al |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 13.74 | 1.37 | 4.14 | 0.208 | 0.189 | 0.047 | 0.05 | 0.807 | 0.037 | 0.066 | 0.024 | Rest |

i. Identifies the relationships between cause and effect of the reality.
ii. Facilitates the understanding of interactions among the factors in the experiment.
iii. Finds the levels at which the controllable factors are to be fixed.

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iv. Minimizes the experimental error.

v. Improves the robustness of the design.

Taguchi's OA technique chooses a fraction of the combinations out of the full factorial design. If we take this study, the number of input parameters chosen were 4 and the number of level are 3. For a full factorial design the number of trials to be performed is $3^4 = 81$, but OA for the same design chooses just set of combinations $L_9$ and $L_{27}$ out of these 81 trials. One can choose $L_9$ for lesser resolution and $L_{27}$ for higher resolution. This proposed experiment is designed using Taguchi's $L_9$ OA technique. The experimental design table for $L_9$ OA is shown in Table 2.

**Table 2 - Experimental layout using $L_9$ orthogonal array**

| Experiment No. | Laser Power (kW) | Cutting Speed (m/min) | Gas Pressure (bar) | Stand Off Distance (mm) |
|---|---|---|---|---|
| 1 | 1 | 1 | 1 | 1 |
| 2 | 1 | 2 | 2 | 2 |
| 3 | 1 | 3 | 3 | 3 |
| 4 | 2 | 1 | 2 | 3 |
| 5 | 2 | 2 | 3 | 1 |
| 6 | 2 | 3 | 1 | 2 |
| 7 | 3 | 1 | 3 | 2 |
| 8 | 3 | 2 | 1 | 3 |
| 9 | 3 | 3 | 2 | 1 |

The input parameters chosen and the levels of each factor are presented in Table 3.

**Table 3 - Input process parameters and their levels**

| Input Parameters | Symbol | Unit | Level 1 | Level 2 | Level 3 |
|---|---|---|---|---|---|
| Laser Power | A | kW | 3 | 3.5 | 4 |
| Cutting Speed | B | m/min | 2.5 | 3 | 3.5 |
| Gas Pressure | C | Bar | 8 | 10 | 12 |
| Standoff Distance | D | Mm | 0.7 | 0.9 | 1 |

The experiments are done using TLC005 Trumpf laser cutting machine. The specifications of the machine are shown in the following Table 4. These experiments are done for 2mm thick and 3mm thick sheets of Al-alloy.

For the purpose of studying the cut quality, a profile has been designed comprising of both linear and polar dimensions as well. The effect of laser cutting process parameters for straight and curved profiles have been studied by Amit Sharma and Vinod Yadava [4,8]. Hence this paper tends to investigate the effect of the control factors for complex profiles having both straight and curved cuts. Figure 3 shows the profile cut for the proposed study.

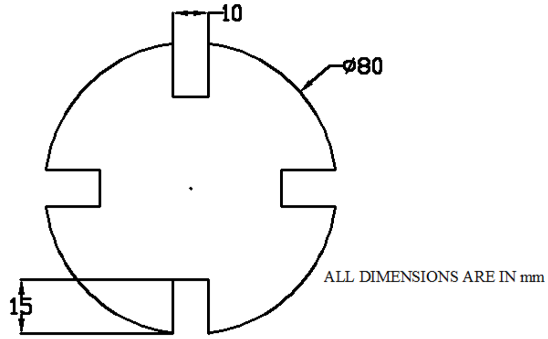


**Fig.3 Laser cut profile**

## IV. MODELLING USING MRA TECHNIQUE

The multiple regression analysis technique is used to find the relationship between the control factors and the measured responses. For this study the regression modelling is done with the help of Minitab 15 software and the corresponding ANOVA calculations for lack of fitness test is also done. The Eqn.(1) and Eqn.(2) shows the relation between the control factors laser power (kW), cutting speed (m/min), assist gas pressure (bar) and nozzle standoff distance (mm) and the responses surface roughness (µm) and kerf width (mm) respectively.

$$Ra = 6.13 - 0.332A - \quad (1)$$

$$Kw = 0.333 + 0.006677A - 0.0165I \quad (2)$$

The corresponding lack of fitness test for the above regression models are shown in Table 4 and Table 5.

**Table 4 – ANOVA for Eqn. (1)**

| Source | Degrees of Freedom | Sum of Squares | Mean Squares | F-value | P-value | $R^2$ value |
|---|---|---|---|---|---|---|
| Regression | 4 | 1.7816 | 0.4454 | 7.6006 | 0.814 | 82.6% |
| Residual Error | 4 | 0.671 | 0.0586 | | | |
| Total | 8 | 2.4526 | | | | |

**Table 5 – ANOVA for Eqn. (2)**

| Source | Degrees of Freedom | Sum of Squares | Mean Squares | F-value | P-value | $R^2$ value |
|---|---|---|---|---|---|---|
| Regression | 4 | 0.0065 | 0.0036 | 8.4071 | 0.893 | 87.08% |
| Residual Error | 4 | 0.0017 | 0.0004 | | | |
| Total | 8 | 0.0083 | | | | |

The F-value for both the regression models are greater than the Table value (for $\alpha = 0.05$) and hence both the models provide significant results. A more important indicator for regression analysis is the $R^2$ value which are well above than 80% which implies that the regression model is fit.

## V. GREY RELATIONAL ANALYSIS

The GRA associated with Taguchi method represents a new approach to optimization. The grey theory is based on the random uncertainty of small samples which developed into an evaluation technique to solve certain problems of system that are complex and having incomplete information. A system for which the relevant information is completely known is a 'white' system, while a system for which the relevant information is completely unknown is a 'black' system. Any system between these limits is a 'grey' system having poor and limited information. GRA, which is a normalization evaluation technique, is extended to solve the complicated multi-performance characteristics [19].

5.1 Data Normalization

In GRA, if a factor's measured a unit, goals, and directions are different the GRA produce incorrect results [9]. Therefore the experimental data gathered must be pre- processed. Data pre-processing is the process of transforming the original sequence to a comparable sequence. For this the experimental data are converted in to normalized values ranging between zero and one. Data normalization is done using one of the following three types based on the response characteristics.

i. " the-larger-the-better"

(3)

ii. "the-smaller-the-better"

(4)

iii. "the-nominal-the-best"

(5)

where is the value after the grey relational data pre-processing, is the largest value of , is the least value of . Table 3 experimental layout using $L_9$ orthogonal array and response characteristics.

The normalized values for the surface roughness and kerf width are presented in the Table 6.

**Table 6 – Normalized Values**

| Trial | Normalized Values | | Δ values | |
|---|---|---|---|---|
| No. | Ra | Kw | **Ra** | **Kw** |
| 1 | 0 | 0 | 1 | 1 |
| 2 | 0.366257341 | 0.785714286 | 0.633742659 | 0.214285714 |
| 3 | 0.788040577 | 1 | 0.211959423 | 0 |
| 4 | 0.656166578 | 0.794642857 | 0.343833422 | 0.205357143 |
| 5 | 0.318739989 | 0.625 | 0.681260011 | 0.375 |
| 6 | 0.540843566 | 0.696428571 | 0.459156434 | 0.303571429 |
| 7 | 0.735718099 | 0.535714286 | 0.264281901 | 0.464285714 |
| 8 | 0.480512547 | 0.375 | 0.519487453 | 0.625 |
| 9 | 1 | 0.517857143 | 0 | 0.482142857 |

5.2 Grey relational coefficient and grey relational grade

After pre-processing the data, a grey relation coefficient is calculated to express the relationship between the original and comparable sequence. The grey relational coefficient ( ) can be expressed using the formulae shown in Eqn. (6)

(6)

Here η is distinguish or identification coefficient: η ε [0,1], η = 0.5 is generally used [9]. Once the grey relational coefficients of the responses are calculated the grey relational grade ( is obtained by calculating the average of the coefficients. The grey relational grade is defined in the Eqn. (7) and the grey relation coefficients and the grey relational grades are tabulated in Table 7.

$$\gamma_i = \frac{1}{n}\sum_{k=1}^{n} \varepsilon_i \qquad (7)$$

**Table 7 - Grey relational coefficient and Grey relational grade**

| Trial No. | ε for Ra | ε for Kw | γ values |
|---|---|---|---|

| | | | |
|---|---|---|---|
| **1** | 0.333333333 | 0.333333333 | 0.333333333 |
| **2** | 0.441017189 | 0.7 | 0.570508594 |
| **3** | 0.702287214 | 1 | 0.851143607 |
| **4** | 0.592534008 | 0.708860759 | 0.650697384 |
| **5** | 0.423276836 | 0.571428571 | 0.497352704 |
| **6** | 0.5212914 | 0.622222222 | 0.571756811 |
| **7** | 0.654208872 | 0.518518519 | 0.586363695 |
| **8** | 0.490442524 | 0.444444444 | 0.467443484 |
| **9** | 1 | 0.509090909 | 0.754545455 |

In grey relational analysis, the grey relational grade is used to show the relationship among the sequences. If the two sequences are identical, then the value of grey relational grade is equal to 1. The grey relational grade also indicates the degree of influence that the comparability sequence could exert over the reference sequence. Therefore, if a particular comparability sequence is more important than the other comparability sequences to the reference sequence, then the grey relational grade for that comparability sequence and reference sequence will be higher than other grey relational grades. Table 7 shows the grey relational coefficients for the both responses and the grey relational grade.

5.3 Response Table for Grey relational grade

The response table of Taguchi method is used to calculate the average grey relational grade for each factor level. The average grey relational grade is computed by grouping the relational grades by considering the factor level for each factors and then by taking the average of these values. The average grey relational grades (γ) for factors A and C at level 1 and 3 respectively can be calculated as follows:

$$\gamma A_1 = (1/3)(\ 0.333333333+ 0.570508594+ 0.851143607) = 0.584995178$$

$$\gamma C_3 = (1/3)(\ 0.851143607+ 0.497352704+ 0.586363695) = 0.644953$$

Similarly calculations were performed for each factor level and response table was generated as shown in Table 8

**Table 8 – Response Table**

| Factors | Average Grey Relational Grade by Factor Level | | | Max - Min |
|---|---|---|---|---|
| | Level 1 | Level 2 | Level 3 | |
| A | 0.584995178 | 0.573268966 | <u>*0.602784211*</u> | 0.029515245 |
| B | 0.45751121 | 0.511768261 | <u>*0.725815291*</u> | 0.268304081 |
| C | 0.45751121 | <u>*0.658583811*</u> | 0.644953335 | 0.201072601 |
| D | 0.528410497 | 0.5762097 | <u>*0.656428158*</u> | 0.128017661 |

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The grey relational grades represent the correlation between the reference and the comparability sequences. The larger the grey relational grade means the comparability sequence exhibits a stronger correlation with the reference sequence. In Table 8, $A_3$, $B_3$, $C_2$ and $D_3$ show the largest value of grey relational grade for factors A, B, C and D respectively. Therefore $A_3B_3C_2D_3$ is the optimal parameter condition for the laser cutting process, i.e. laser power is 3.5kW, cutting speed is 3.5m/min, assist gas pressure is 10 bar and standoff distance is 1mm.

When the last column of the response table shown in Table 6 is studied, it is very obvious that the difference between the maximum and minimum grey values of the factor B i.e. cutting speed is bigger than the other three factors, which clearly implies that the cutting speed has a stronger impact on the multi performance characteristics than other factors.

## VI. RESULTS

In the earlier steps the optimization process using GRA is done and the optimal values of the input parameters are arrived. To make a better and quick understanding of the results, the experimentation data are presented in a graphical way with the aid of surface graphs.

These surface graphs show the combination effect of two control factors on each response at a time. The surface graphs clearly exhibit the change in the surface roughness or kerf width for every decrease or increase in each level of the input parameters. The Figure 4 to Figure 7 shows the effect of the various input parameters chosen on the output responses.

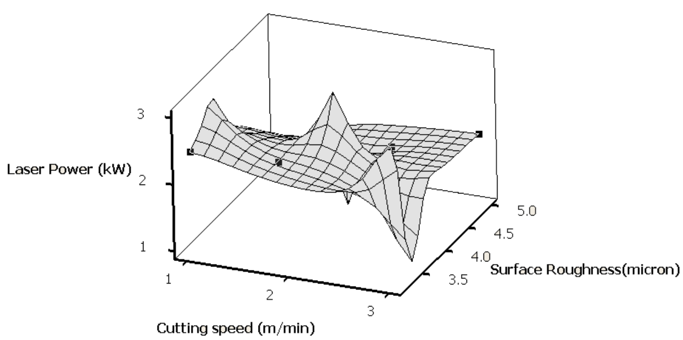


**Fig. 4 – Surface graph for surface roughness Vs Laser power & cutting speed**

The above figure shows clearly the effect of laser power and cutting speed on the surface roughness of the laser cut. As the cutting speed is lesser the surface roughness is also lesser. The surface roughness dips and then rises only slightly as there is an increase in the cutting speed. Hence the cutting speed and laser power can be maintained at level 3 which is unanimous with the optimal values.

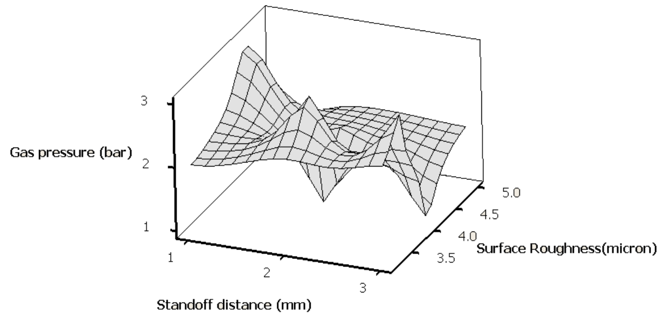


**Fig. 5 – Surface graph for surface roughness Vs gas pressure & standoff distance**

The inferences from the above figure are middle value of gas pressure and high value of standoff distance gives the least surface roughness.

It is very evident from the Figure 6 that the maximum cutting speed and minimum laser power gives the optimal kerf width.

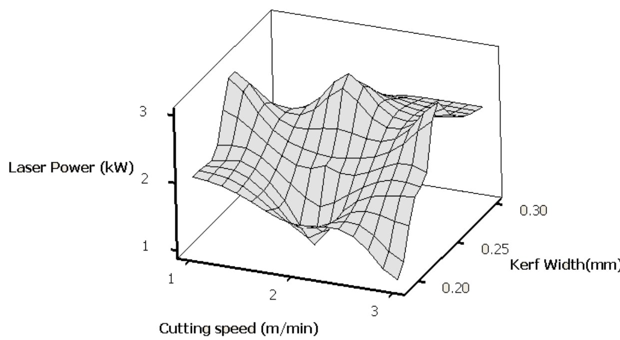


**Fig. 6 – Surface graph for kerf width Vs Laser power & cutting speed**

6.1 Validation

The confirmation experiment is performed in order to prove the proposed study by using the optimal parameters obtained using grey relational analysis technique. As shown in Table 9 the obtained response out of the optimal parameter cutting shows a reduction in surface of around 20.64%, which is a remarkable improvement in quality. Regarding kerf width the kerf width has improved i.e. reduced to the extent of 33% as of the average kerf width attained in the earlier experiments.

**Table 9 – Responses before and after optimization**

| Description | γ value |
|---|---|
| Average grey relational grade before optimization | 0.581519 |
| Grey relational grade after optimization | 0.732845 |
| Improvement in cut quality | 20.64% |

## VII. CONCLUSION

This paper discussed the experimental investigation on laser cutting of thick non ferrous metal sheet i.e. aluminium alloy BS 1100 2mm thick sheet using $CO_2$ laser. The effect of the control factors laser power, cutting speed, assist gas pressure and standoff distance on the cut quality characteristics surface roughness and kerf width were analyzed. The optimal parameters to obtain a better cut were obtained by optimizing the entire process using grey relational analysis technique. The obtained results have shown considerable improvement in the quality characteristics.
This analysis can be further taken up for a detailed study on several other factors such as nozzle diameter, assist gas etc.

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